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by
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Global processing of satellite sounding radiances in a numerical weather prediction system

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SUMMARY

This paper gives an account of the Global Soundings System (GLOSS), which is the new method introduced at the Meteorological Office at Bracknell for the processing of global TOVS radiance data for assimilation into numerical weather prediction (NWP) models. The assimilating NWP models themselves provide the prior information necessary to infer temperature and humidity information from radiances. After some historical background, the GLOSS processing is described, noting in particular the differences from similar work elsewhere. Results are then presented from NWP impact studies of the assimilation of temperature profiles derived from satellite soundings. An advantage is demonstrated for the GLOSS temperature retrievals relative to the retrievals distributed by NESDIS and produced from the same radiance data. The advantage for GLOSS is clear and consistent in the extratropical regions of the northern hemisphere and, especially, the southern hemisphere. In the tropics the results are more mixed. The paper concludes with an outline of the expected future developments of this work.

1. INTRODUCTION

Temperature profile information retrieved from instruments flown on the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting satellites have been made available by NOAA's National Environmental Satellite and Data Information Services (NESDIS) since the early days of the satellite TIROS-N, launched in October 1978. Over the years, there have been only minor changes in the instrumentation, known as the TIROS Operational Vertical

Sounder (TOVS). However there have from time to time been significant changes in the NESDIS processing of the TOVS measurements. In addition, NESDIS have made their TOVS retrievals available at progressively higher horizontal resolution: first 500km, then 250 km and later 120km.

The NESDIS TOVS retrievals were first used in numerical prediction experiments associated with the Global Weather Experiment (December 1978 - November 1979 inclusive). It quickly became established that the retrievals had a major positive impact on numerical weather prediction (NWP) in the extratropical southern hemisphere, and this position has remained unchanged. In the northern hemisphere, however, impact studies, taken as a whole, have given inconclusive results on the benefits of NESDIS TOVS retrievals. The differing results for the two hemispheres are quite plausible given the almost complete lack of other upper air information in much of the southern hemisphere.

As is well known, the inversion of satellite sounding radiances is an underdetermined problem whose solution requires the provision of prior information, often in the form of background temperature and humidity profiles. Reporting on work carried out at the European Centre for Medium Range Weather Forecasts (ECMWF), Eyre et al. (1993) suggested that the problems in obtaining a positive impact from the NESDIS retrievals in the northern hemisphere have arisen principally from the use of insufficiently accurate prior information in the NESDIS processing. They showed that if they assimilated a subset of the TOVS radiance data (as preprocessed by NESDIS) within the ECMWF NWP system, using the ECMWF NWP model to provide the background profiles for the inversion, then a consistent positive TOVS impact was found in the northern hemisphere. (Surprisingly at first sight, the impact in the southern hemisphere was negative relative to that of NESDIS retrievals, for reasons which the authors discuss.)

The work reported in the present paper follows Eyre et al. (1993) in using the assimilating NWP model to provide the background profiles. In this case the relevant models are operational forecast versions of the Meteorological Office's unified forecast/climate model (Cullen, 1993): the global model and the limited area model (LAM). Data assimilation is performed using the analysis correction scheme described by Lorenc et al. (1991).

The differences of the present work from that described by Eyre et al. (1993) are principally in the retrieval of information from additional TOVS channels and in the procedures to deal with cloud affected radiances. The resulting Global Soundings System (GLOSS), described below, has been demonstrated to provide temperature profiles that have a positive impact on numerical forecasts, relative to the NESDIS retrievals, in both hemispheres. This is despite an improvement in the quality of the NESDIS retrievals noted late in 1992.

The characteristics of the TOVS instrument package have been published on many occasions (see for example Smith et al., 1979). For the moment it is sufficient to recall that the package consists of the Stratospheric Sounding Unit (SSU, 3 channels), the High-resolution Infrared Radiation Sounder (HIRS, 20 channels) and the Microwave Sounding Unit (MSU, 4 channels).

2. HISTORICAL BACKGROUND

Beginning in the early 1980s, locally produced TOVS retrievals became available at Bracknell through the processing of direct read-out data in a system known as the Local Area Soundings

System (LASS) - see Eyre and Jerrett (1982). Here we briefly review the history of LASS which provides important background to an appreciation of GLOSS.

The first version of LASS, implemented in 1983, was essentially the International TOVS Processing Package (ITPP) imported from the Cooperative Institute for Meteorological Satellite Studies at Madison, Wisconsin. The emphasis was on the provision of soundings for the local area of a similar nature to those available from NESDIS but in a more timely fashion and at higher horizontal resolution.

The first significant local development of the ITPP was the use in the linear retrieval algorithm of climatological information specific to the LASS area.

Early study of the LASS results suggested that cloud clearing was one of the main sources of error. This stimulated research that culminated in a new cloud clearing scheme (Eyre and Watts, 1987).

A primary aim in the establishment of LASS had been the provision of useful data for the NWP system. LASS data were assimilated for a period beginning in September 1984, but misgivings persisted about the impact of the climatological component entering the retrievals as prior information (Lorenc et al., 1986). It became recognised that the accuracy of available NWP results was such that more accurate retrievals could be obtained if NWP profiles were used to provide the necessary prior information for the inversion (Eyre et al., 1986). This being accepted, the linear inversion can be written as follows.

$$x - x^b = W.[y^{cm} - y(x^b)] \tag{1}$$

where x is the retrieved profile vector, x^b is its NWP background value, y^{cm} is the vector of cloud-cleared measured radiances, and $y(x)$ is the forward radiative transfer model enabling background radiances $y(x^b)$ to be calculated from the background profile x^b. The inverse matrix, W, defined as

$$W = B.K^T.(K.B.K^T + O + F)^{-1} \tag{2}$$

is that giving the most probable solution on the assumption of Gaussian errors with the expected covariance matrices B for errors in the background profiles, O for errors in the measurements and F for errors in the forward model. K, which represents the matrix of partial derivatives of $y(x)$ with respect to the elements of x, is assumed independent of x for the linear algorithm.

This approach was implemented using the then current LAM background profiles in November 1987 and LASS data were assimilated operationally from May 1988 until October 1992. Their impact was studied by Bell and Hammon (1989) who found it to be small and positive and a definite improvement relative to NESDIS soundings which gave a negative impact at that time.

When the LASS first began using NWP background profiles, the organisation of the processing was such that forecasts for up to 15 hours ahead were used as backgrounds. In February 1990 a closer coupling between LASS and the NWP system was introduced (Gadd, 1990) which reduced this maximum to around 8 hours. Time interpolation of NWP backgrounds was also introduced at this stage.

In October 1992 assimilation of LASS was discontinued due to disquiet about interaction with NWP background biases. Study of this problem highlighted two features (P C Dibben, personal communication). Firstly, given that the present interface between satellite soundings and NWP consists of pressure level data, it is important that the calculation of pressure level temperatures from NWP model level data does not produce large biases. Secondly, it is essential to ensure strict consistency in all transformations and interpolations from model data to pressure level data throughout the NWP and satellite sounding systems; otherwise marked artificial biases can

easily be introduced. Introduction of operational NWP changes to deal with these points was completed in May 1993.

Meanwhile, Eyre (1989a) had developed a non-linear, variational, method for the inversion of cloudy TOVS radiances. This involves an iterative algorithm to minimize a penalty function, J.

$$J(x) = (x - x^b)^T.B^{-1}.(x - x^b) + [y^m - y(x)]^T.(O + F)^{-1}.[y^m - y(x)] \quad (3)$$

The nth iteration may be written as follows.

$$x_{n+1} - x^b = W_n.[y^m - y(x_n)] + W_n.K_n.(x_n - x^b) \quad (4)$$

W_n is as defined in Eq 2 but with K replaced with K_n. In Eyre's application of this algorithm, y^m are the measured radiances (cloud-affected and without correction for scan angle, known technically as level 1b data) whilst the profile vector x includes not only temperatures (T) and humidities - held as log of mixing ratio (q) - but also fractional cloud amount (n), cloud top pressure (p_t) and microwave surface emissivity (ϵ_s). Preliminary values of n and p_t are retrieved using HIRS channels 7 and 8 before the iterations using all channels.

The inversion of cloudy radiances has not yet been established as an operational method, principally it is thought due to an inherent ambiguity between n and p_t. However the non-linear variational algorithm itself has great generality. Note for example that, when applied to clear radiances, and with $x_1 = x^b$, the first iteration yields the linear solution given in Eq 1 above, but with the advantage that K is a function of the background profile x^b. Even when restricted to clear radiances, the non-linear algorithm offers significant advantages compared with the linear as regards humidity retrievals (Gadd, 1993).

The evolution of TOVS processing within LASS, outlined above, raised questions at Bracknell about the policy for global soundings. The availability of radiances (albeit after NESDIS pre-processing) with global coverage (collocated with the NESDIS 120km retrievals) opened the possibility of developing a global system based on similar principles to LASS. The resulting system - GLOSS - is described in section 3. The first version of GLOSS was implemented for evaluation purposes in August 1992. On the basis of the results presented in section 4, operational assimilation of GLOSS profiles was introduced in January 1994, both in the global model and in the LAM.

3. DESCRIPTION OF GLOSS

(a) The available TOVS radiance data

The Global Soundings System (GLOSS) is designed to provide satellite sounding data with global coverage for assimilation into the NWP models at Bracknell. GLOSS depends on the transmission to Bracknell of global TOVS data from NESDIS in Washington. Although usually referred to as radiances, the sounding data are in fact transmitted in the form of brightness temperatures. Note that Eqs 1-4 above remain applicable simply by defining y to represent brightness temperature rather than radiance.

The NESDIS brightness temperatures currently available are known as the cloud-cleared brightness temperatures. However, a more detailed statement is required to understand their nature. The data are the result of NESDIS processing as follows.

- The HIRS brightness temperatures have been corrected for scan angle, ie corrected to nadir viewing.

- The brightness temperatures for HIRS channel 8 ($11.11\mu m$, the best infrared window channel) have been corrected for attenuation by atmospheric water vapour (ie the values provided are estimates of those expected if the atmosphere were completely dry).

- Each HIRS field of view has been classified as clear, partly cloudy or cloudy. With the exception of the stratospheric channels, 1-3, HIRS brightness temperatures are not provided at fields of view classified as cloudy. At fields of view classified as partly cloudy, the brightness temperatures provided for HIRS channels other than 1-3 are the result of NESDIS cloud-clearing calculations.

- The brightness temperatures for MSU channels 2-4 have been corrected for scan angle (including asymmetry), antenna gain pattern, and surface emissivity (ie the values provided are estimates of those expected if $\epsilon_s = 1$). All MSU brightness temperatures have been mapped to HIRS locations.

- The SSU brightness temperatures have been corrected for scan angle and mapped to HIRS locations. The SSU mapping includes provision of values at wider scan locations and values for satellites that do not carry the SSU instrument.

- The horizontal resolution has been reduced to approximately 120km by selecting one from 3x3 arrays of HIRS fields of view, with preference given to clear fields of view.

(b) Selection of TOVS data for GLOSS processing

There are 27 TOVS channels in total, one of which (HIRS channel 20, $0.69\mu m$) is in the visible part of the spectrum. Of the remaining 26 channels, the following 6 are not used directly in GLOSS at present.

- HIRS channel 9 ($9.71\mu m$) is primarily an ozone-measuring channel. It is used by NESDIS in an algorithm to retrieve total column ozone, the values of which are made available along with the TOVS brightness temperatures.

- HIRS channels 16 ($4.40\mu m$) and 17 ($4.13\mu m$) are excluded for historical reasons. Their use should be reconsidered now.

- HIRS channels 18 ($4.00\mu m$) and 19 ($3.76\mu m$) are significantly sensitive to reflected radiation that is not represented in the version of the radiative transfer model used here. Research on the use of channel 19 has been reported by Watts (1993).

- MSU channel 1 (50.31 GHz) is mainly useful in determining the microwave emissivity of the underlying surface. It is used by NESDIS in emissivity correction algorithms for MSU channels 2-4, and it is the corrected brightness temperatures for these channels that are made available.

The channels used in GLOSS are those shown in Table 1. Note that the cloudy and partly cloudy categories are taken together as 'not clear'. Compared with Eyre et al. (1993), the differences in the channels used are as follows.

(i) The SSU channels are included.

	NESDIS classification	
	clear	*not clear*
SSU channels	1-3	1-3
HIRS channels	1-8, 10-15	1-3
MSU channels	2-4	2-4
number of channels	20	9

Table 1: TOVS channels used in GLOSS, according to NESDIS classification of HIRS fields of view.

(ii) HIRS channel 8 is included. To achieve this, the channel 8 brightness temperatures as received are decorrected to remove the water vapour attenuation correction applied by NESDIS. The decorrection code (M Uddstrom, personal communication) uses separate coefficients for each NOAA satellite. NESDIS do not apply any correction if the column is judged to be very dry according to certain criteria, and the decorrection is not applied in such cases.

(iii) HIRS channels 4-7 (and 8, not used by Eyre et al., 1993) and 10-15 are excluded if the field of view is classified by NESDIS as partly cloudy. This is because the data in such cases are the products of NESDIS cloud clearing calculations. Since the quality of these calculations is disputed, these modified HIRS brightness temperatures are not used in GLOSS.

The NESDIS brightness temperatures identified in Table 1, with HIRS channel 8 decorrected, are referred to below as the input brightness temperatures.

(c) Background profiles and brightness temperatures

Input brightness temperatures for the operational NOAA satellites, NOAA-11 and NOAA-12 at the time of writing, are organised in 6-hour time intervals for the global model or 3-hour intervals for the LAM, along with collocated NWP profiles valid at the middle of the interval, horizontally interpolated from the global model or the LAM as appropriate. The NWP temperatures are provided at 18 levels from 1000hPa to 10hPa and the NWP humidities at 7 levels from 1000hPa to 300hPa. In addition, NWP data are used to provide background values of skin temperature, screen temperature, screen humidity and surface pressure.

The background profiles $\boldsymbol{x}^b$ are completed by interpolation of temperature and humidity to other levels, and extrapolation of temperature upwards from 10hPa, to obtain temperatures at the 40 pressure levels and humidities at the 15 pressure levels required by the radiative transfer model RTTOV (Eyre, 1991). (There is extrapolation of humidity internally within RTTOV for levels above 300hPa.)

Background clear brightness temperatures are then calculated using RTTOV. The NESDIS retrieved total column ozone is used as an input to RTTOV where it is available, and where it is not a regression method is used to estimate total ozone from the 70hPa background temperature. The NESDIS ozone value is available for all but a small subset of the soundings classified as clear, whilst for the channels used when a sounding is classified as not clear there is very little effect of ozone.

A modified version of the air-mass dependent bias correction algorithm due to Eyre (1992) is applied. MSU channels 2-4 and HIRS channel 1 are used as predictors of bias corrections to the differences between the input brightness temperatures and the background clear brightness temperatures for all the channels listed in Table 1. The regression coefficients required to obtain

these relative bias corrections are calculated off-line and updated each month. For the calculation of these coefficients, a latitudinally representative set of quality controlled fields of view over the sea is selected. Only fields of view classified by NESDIS as clear, and for which no cloud is detected by GLOSS, are used in the calculation of the coefficients. Separate coefficients are calculated for each satellite.

(d) Inversion

The inversion is carried out using the non-linear algorithm based on Eq 3 above.

The soundings classified by NESDIS as clear are treated as potentially cloudy. Evidence in support of this caution is given by Rizzi et al. (1992). Thus the full inversion algorithm is applied to the 20 channels listed in Table 1. The preliminary calculation of cloud amount and cloud top pressure using channels 7 and 8 serves as a screen for residual cloud undetected by NESDIS.

For the soundings classified by NESDIS as not clear, the non-linear algorithm is applied to those channels that are assumed unaffected by cloud, ie the 9 channels listed in Table 1.

Referring to Eq 4, RTTOV is used to calculate the brightness temperatures $y(x_n)$ and the Jacobian matrix K_n each iteration with the effects of any residual cloud included. The relative bias corrections mentioned above remain unchanged during the iterations and so for convenience they are applied to the input brightness temperatures to form the y^m of Eq 4.

The matrix of measurement plus forward model error covariances $(O + F)$ is diagonal. The diagonal elements are calculated using the standard values of the radiometric errors given by Eyre (1989a) and the value of 0.4K for the expected rms forward model errors in each channel. Revised estimates of these covariances have recently been made, but these have not yet been implemented.

The matrix of background error covariances (the B matrix) is that given by Eyre (1989a) and was determined empirically, using radiosonde observations up to 50hPa in the LASS area as truth, and then extrapolated to higher levels using regression relationships. Again, there is evidence that the diagonal elements in the B matrix should be revised (with the off-diagonal elements modified accordingly; evidence for revision of the correlations is lacking as yet). For the present work however it was decided to retain the 1989 values pending a thorough review. The target here is to use values consistent with the rest of the assimilation, where synoptic-dependent background errors have been introduced (Parrett, 1992).

(e) Quality control

Following Eyre (1989b), a retrieval is flagged for rejection by the data assimilation if the difference between the input brightness temperature (with the relative bias correction applied) and the brightness temperature corresponding to the retrieved profile, known as the solution brightness temperature, in any channel exceeds 4 times the expected rms brightness temperature error in that channel (ie the square root of the appropriate diagonal element from the $O + F$ matrix). Retrievals are also flagged if the inversion does not converge after 7 iterations.

(f) Monitoring

The background and retrieved profiles along with the NESDIS brightness temperatures, the input brightness temperatures (with the relative bias corrections applied), the background brightness

temperatures, the solution brightness temperatures and the quality control flags are stored for subsequent monitoring. Facilities have been developed both for monitoring using NWP data and for monitoring using radiosonde observations.

4. NWP IMPACT STUDIES

The impact of GLOSS has been studied by means of experimental runs of the NWP suite in parallel with the operational suite. In the experimental runs, the NESDIS 120km temperature retrievals were replaced globally with the GLOSS 120km data. Note that the 120km data are used at full resolution, without further thinning such as that adopted by Eyre et al. (1993). This is possible as a result of assimilation modifications introduced by Bell (1992).

Both operationally and in the experiments the 120km soundings were assimilated only over the sea, including sea-ice, whilst over land NESDIS 500km retrievals were assimilated, but only at levels above 100hPa. TOVS humidity retrievals were not assimilated either in the experiments or in the operational runs.

The GLOSS temperature profiles as presented to the assimilation consist of values at 18 levels from 1000hPa to 10hPa. Note that the inclusion of the SSU data permits the use of the profiles right up to 10hPa, whereas Eyre et al. (1993) retained NESDIS temperatures above 30hPa. The NESDIS temperatures used in the operational runs are layer mean values for 12 layers between 1000hPa and 10hPa.

Results are presented here from two periods of parallel running, one in June 1993 and the other in November 1993.

The quality of the data assimilations has been assessed by verifying background (6 hour) forecasts against radiosonde observations. Statistics on the differences of background wind forecasts from radiosonde winds, stratified according to the observed wind speed, have been calculated by R Graham (personal communication). The global results are shown in Figure 1 for the June period and Figure 2 for the November period. These show a consistent benefit from GLOSS in both seasons. Importantly, the benefit increases with increasing speed of the observed wind and amounts to a nearly 10 percent reduction in the rms errors for jets of $50ms^{-1}$ or greater. The statistics have also been studied for the latitude bands 90N-45N, 45N-15N, 15N-15S, 15S-45S and 45S-90S. The benefit from GLOSS was seen in all five latitude bands.

For the November run, three day forecasts were also assessed. The first 8 days of the experiment were treated as a warm-up period during which the experimental and operational analyses could diverge from one another. The subsequent 10 cases (10 - 19 November) were included in the verification statistics. Statistics were calculated for 90N-30N, 30N-30S and 30S-90S.

The rms forecast scores for GLOSS were better than the operational ones in the majority of cases (288 out of 378, taking together rms errors for heights, temperatures and vector winds at 7 levels from 850hPa to 100hPa and for days 1-3, versus observations and versus analyses for the three verification areas). There were majorities in favour of GLOSS in all three areas: 117 out of 126 in 90N-30N, 72 out of 126 in 30N-30S, and 99 out of 126 in 30S-90S.

Table 2 gives a full summary of the numbers of positive rms impacts. Measured against analyses,

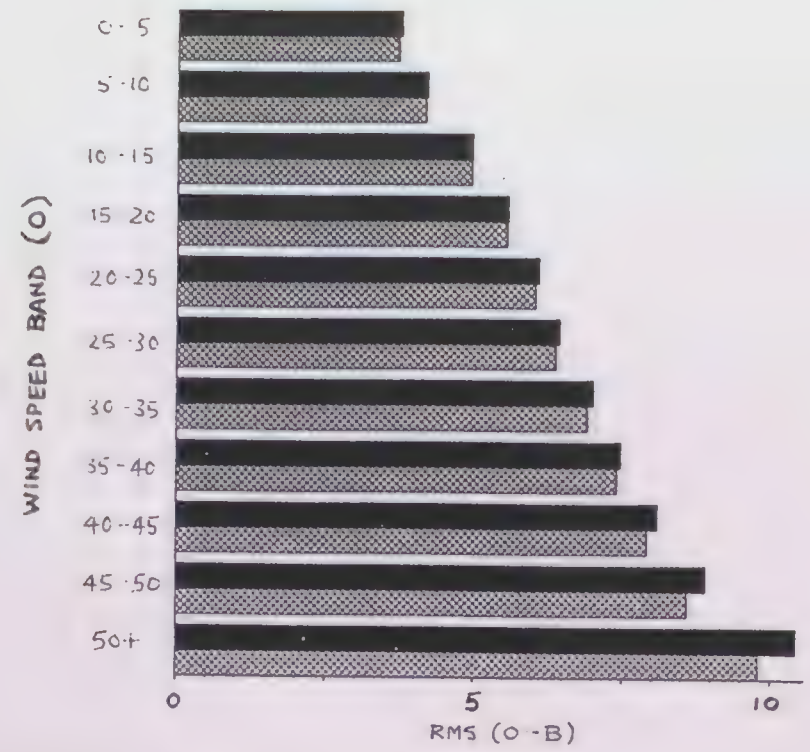

Figure 1: Global rms fit of background (B) winds to radiosonde observations (O), 22-30 June 1993. Solid bars: operational. Hatched bars: GLOSS trial. Units: ms^{-1}

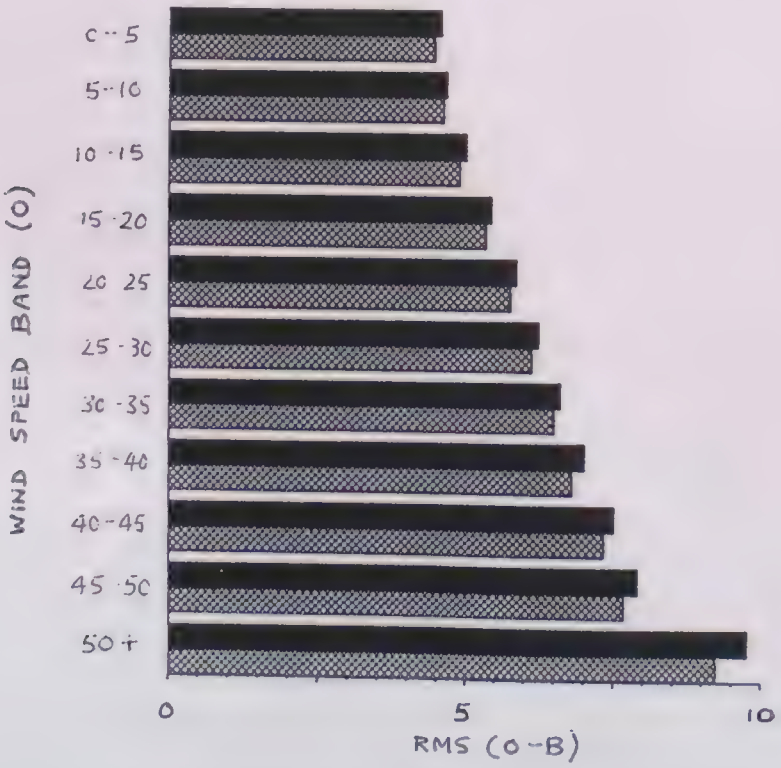

Figure 2: Global rms fit of background (B) winds to radiosonde observations (O), 10-19 November 1993. Solid bars: operational. Hatched bars: GLOSS trial. Units: ms^{-1}

area	*field*	*verification against*	
		analyses	*radiosondes*
90N-30N	height	21	19
	temp	21	19
	wind	18	19
30N-30S	height	9	20
	temp	15	14
	wind	6	8
30S-90S	height	21	21
	temp	18	10
	wind	16	13

Table 2: Numbers of positive rms impacts for GLOSS trial. The maximum score is 21 (7 levels x 3 forecast periods).

an overall positive impact of GLOSS on forecasts was seen in 90N-30N and 30S-90N for all variables and for temperatures in 30N-30S, whilst a negative impact was seen for heights and winds in 30N-30S.

Measured against observations, an overall positive impact of GLOSS on forecasts was seen in 90N-30N for all variables, for heights and temperatures in 30N-30S and for heights and winds in 30S-90S, whilst a negative impact was seen for winds in 30N-30S and for temperatures in 30S-90S.

The small numbers of radiosonde observations available for verification purposes in 30N-30S (around 150) and especially in 30S-90S (around 30) compared with 90N-30N (around 400) must be kept in mind. Thus verification against observations in 30S-90S is likely to be unrepresentative of the area as a whole and more weight must be given to verification against analyses.

The results in the two extratropical areas are clearly very good for GLOSS. The evolution in time of 500hPa height and sea level pressure forecast errors is shown in Figure 3 and Figure 4 for 90N-30N and in Figure 5 and Figure 6 for 30S-90S. In all cases there is a consistent and increasing positive impact of GLOSS during the forecast period. Expressed as increases in forecast period for a given level of accuracy, the positive impacts of GLOSS on 3 day forecasts implied by Figures 3-6 are approximately 4, 5, 11 and 8 hours respectively.

The vertical profiles of the rms height errors of the 3-day forecasts in are shown in Figure 7 for 90N-30N and Figure 8 for 30S-90S. A positive impact from GLOSS is seen at all levels.

Information on the consistency of the impact of GLOSS from case to case is given in the scatter plots of rms errors of operational and experimental 3-day forecasts of 500hPa height for 90N-30N in Figure 9 and for 30S-90S in Figure 10. There is a clear positive impact from GLOSS in 6 out of 10 cases in 90N-30N and in 8 out of 10 cases in 30S-90S.

The results at low latitudes (30N-30S) are more mixed. A majority of the impacts on rms scores are positive but, compared with the extratropical areas, there is less consistency of impact from variable to variable and from level to level. It is expected that the impact in the tropics will be sensitive to the assimilation of TOVS humidity data and the situation will be reviewed after that further development of GLOSS has been implemented.

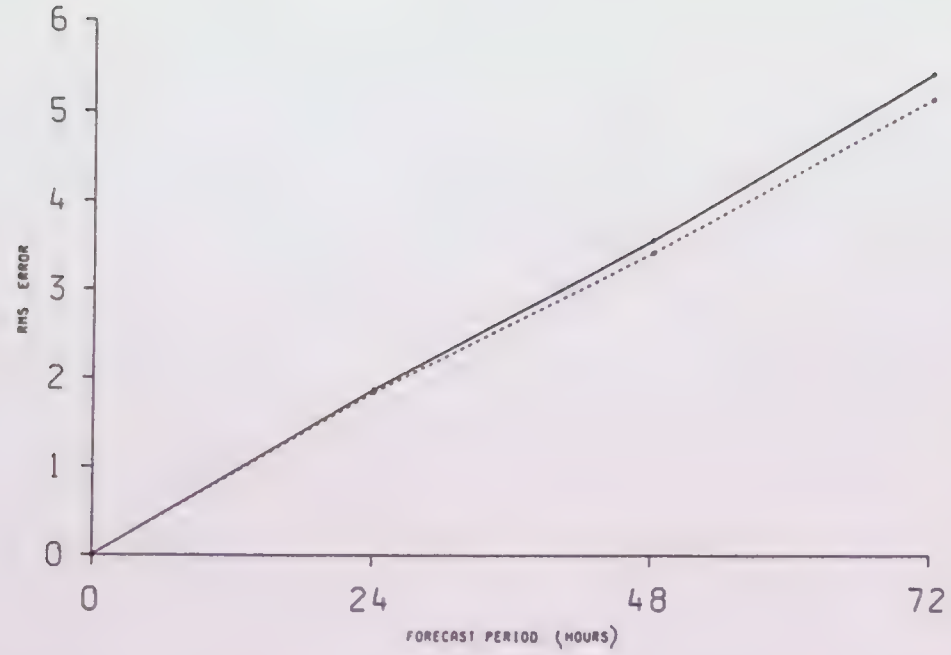

Figure 3: Evolution of rms errors (dam) of 500hPa height forecasts in 90N-30N, measured against analyses, 10-19 November 1993. Full line: operational. Dashed line: GLOSS trial.

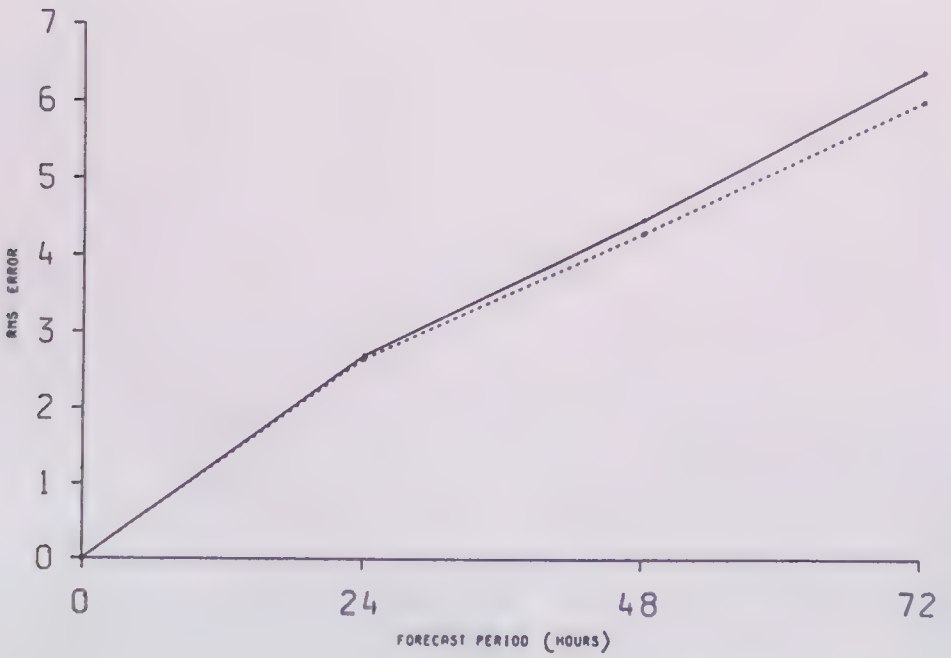

Figure 4: Evolution of rms errors (hPa) of sea level pressure forecasts in 90N-30N, measured against analyses, 10-19 November 1993. Full line: operational. Dashed line: GLOSS trial.

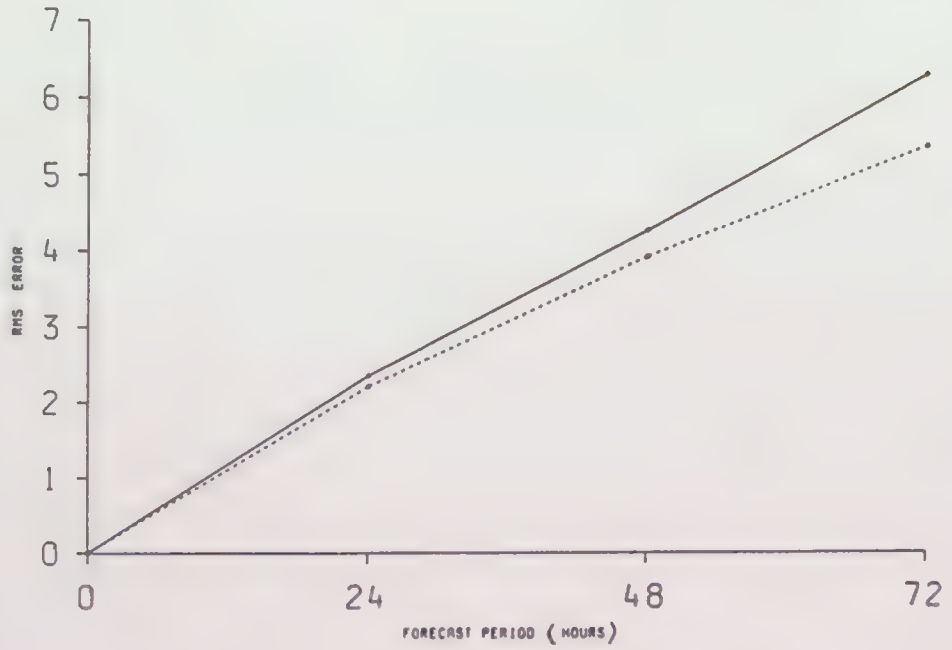

Figure 5: Evolution of rms errors (dam) of 500hPa height forecasts in 30S-90S, measured against analyses, 10-19 November 1993. Full line: operational. Dashed line: GLOSS trial.

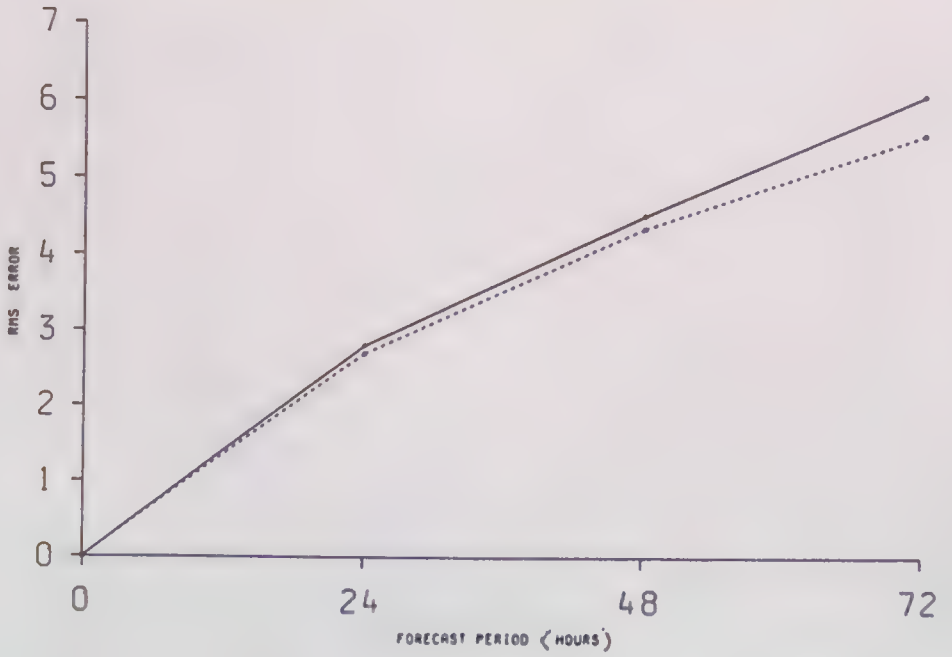

Figure 6: Evolution of rms errors (hPa) of sea level pressure forecasts in 30S-90S, measured against analyses, 10-19 November 1993. Full line: operational. Dashed line: GLOSS trial.

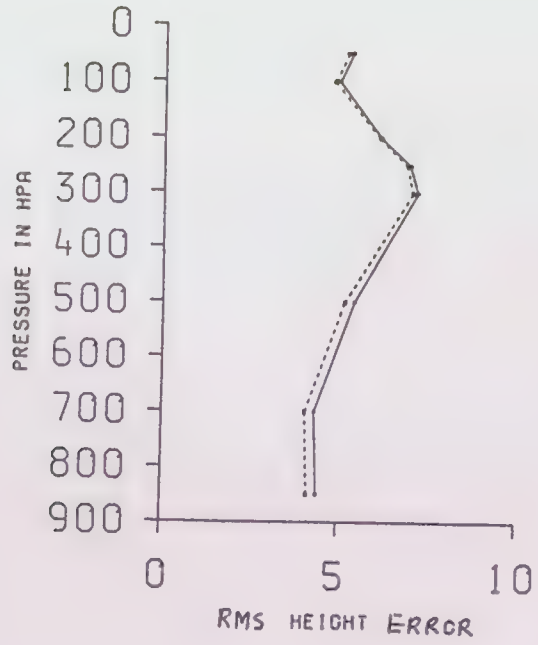

Figure 7: RMS height errors (dam) for 3-day forecasts in 90N-30N, measured against analyses, 10-19 November. Full line: operational. Dashed line: GLOSS trial

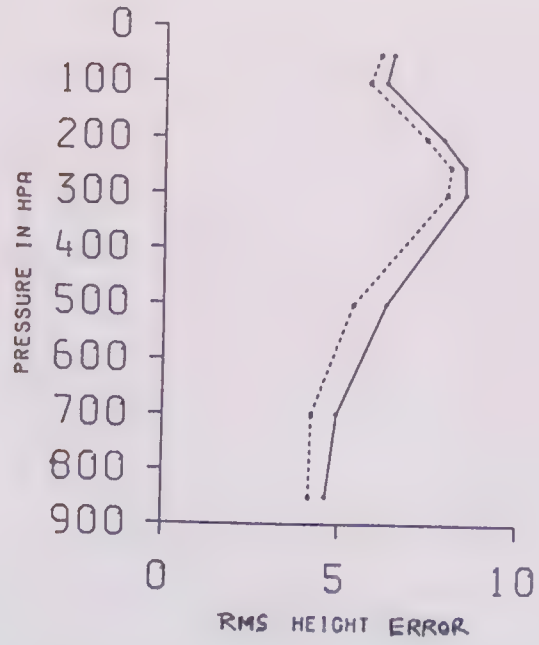

Figure 8: RMS height errors (dam) for 3-day forecasts in 30S-90S, measured against analyses, 10-19 November. Full line: operational. Dashed line: GLOSS trial.

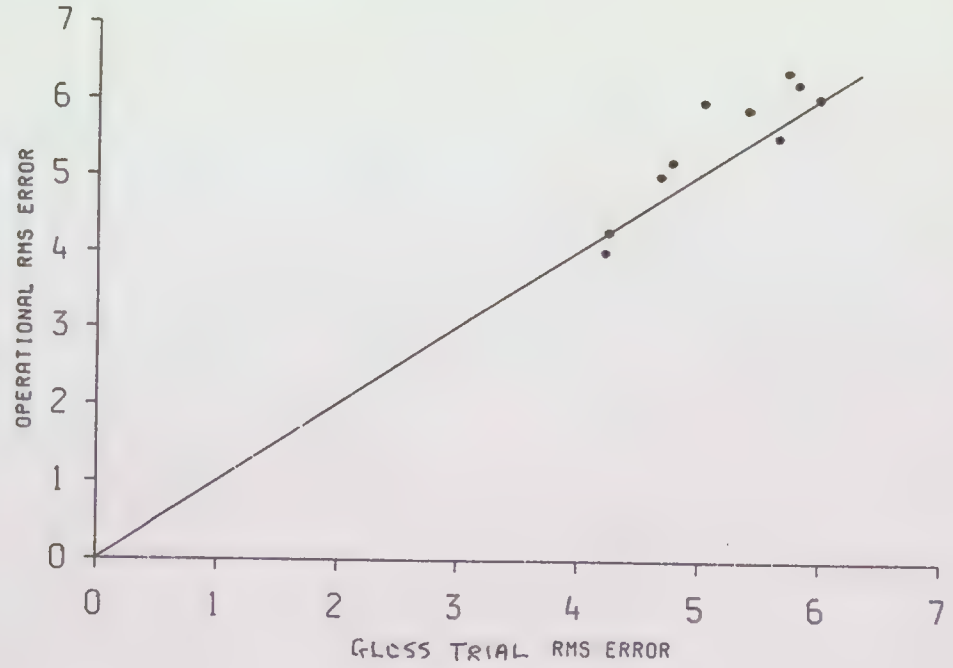

Figure 9: Scatter of rms errors (dam) of 3-day forecasts of 500hPa height in 90N-30N, measured against analyses, 10-19 November 1993

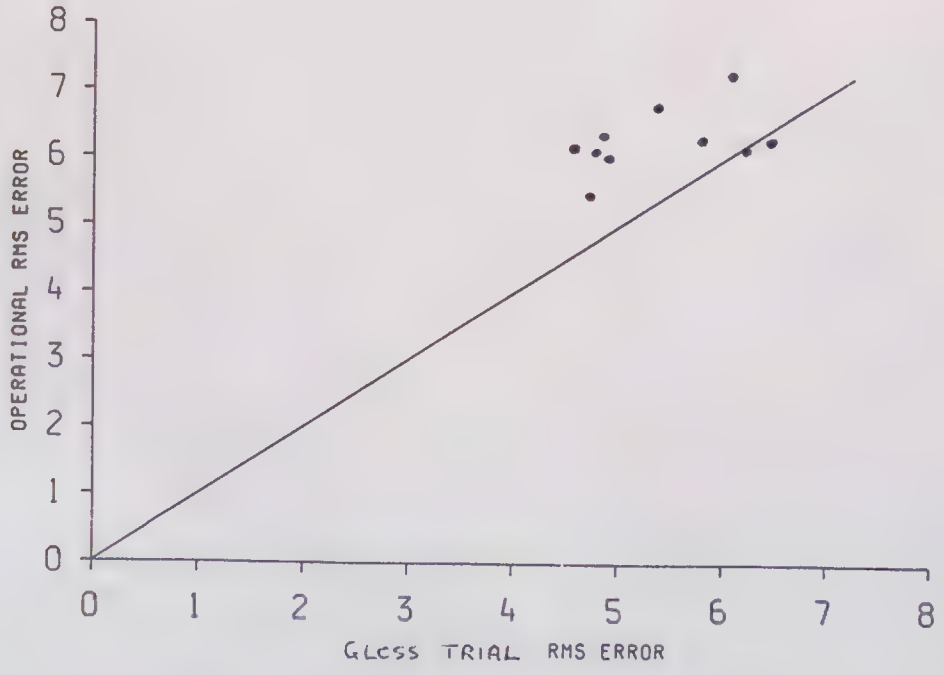

Figure 10: Scatter of rms errors (dam) of 3-day forecasts of 500hPa height in 30S-90S, measured against analyses, 10-19 November 1993

In addition to the objective verification statistics presented above, synoptic charts of sea level pressure and 250hPa height from the GLOSS trial in November 1993 have been compared by R Grant (personal communication) with charts from operational forecasts. A feature of note was that the GLOSS analyses at 250hPa often produced more amplitude in and stronger flow around large scale troughs and ridges. It was found difficult to arrive at an overall subjective judgement on the relative accuracy of the GLOSS forecasts.

Based on the objective results, a decision was made to assimilate GLOSS profiles operationally in the global model and in the LAM. This decision was implemented on 25 January 1994.

5. FUTURE WORK

(a) Short-term developments

The following developments to GLOSS are envisaged in the short-term.

1. Assimilation of TOVS humidity data. The usefulness of HIRS channels 11 and 12 in monitoring changes in NWP humidity fields has already been demonstrated (Renshaw, 1993).

2. Revision of error covariance matrices (see comments in section 3).

3. Modification of increments and weights in the assimilation to take approximate account of correlated errors of retrievals and NWP backgrounds (Lorenc et al., 1986).

4. More sophisticated quality control, following up the approach of Barwell and Young (1993).

(b) Target System

The work leading to the system described in section 3 has been guided by a target TOVS system. This has four important features.

(i) Inversion of cloudy radiances

Inversion of cloudy TOVS radiances is the objective for GLOSS. The principle underlying this is that the fullest possible use should be made of the HIRS measurements. In methods that have been implemented to date, considerable portions of the HIRS data are discarded.

A further motivation for the inversion of cloudy radiances, of course, is the retrieval of cloud information along with the temperature and humidity information. Cloud information is likely to be increasingly useful as input to NWP systems.

(ii) Use of AVHRR data for soundings

Although designed for the provision of satellite imagery, data from the AVHRR (Advanced Very High Resolution Radiometer) instrument on the NOAA spacecraft could very usefully complement TOVS in soundings work. The best approach is to map the AVHRR pixels to each HIRS field of view. Advantage can be taken of AVHRR algorithms that classify the pixels as clear, cloudy or mixed. Thus by processing the set of AVHRR pixels for each HIRS field of view it is possible to obtain estimates of clear and cloudy radiances for each AVHRR channel.

These AVHRR data, used along with TOVS, should be very helpful in improving the retrieval of cloud information. In this way the problem of cloud amount/top ambiguity may be controlled more closely, with benefits for temperature and humidity information.

(iii) Global level 1b data

The developments noted in this section require the availability of level 1b TOVS data and associated AVHRR data. (Level 1b signifies data at the original observation locations that has been calibrated, earth-located, and perhaps subjected to internal quality control checks). For LASS it is straightforward in principle to calculate the required level 1b data from the direct read-out data. For GLOSS these developments depend on arrangements to receive global level 1b TOVS data (with associated AVHRR data) from NESDIS.

In the target system the role of LASS is to provide an earlier delivery of the local data. This will be fulfilled simply by the calculation of the local 1b data and their storage in a global 1b database. Full HIRS resolution globally is the target.

(iv) Inversion embedded in the assimilation

An attractive possibility in the current assimilation environment would be to repeat the inversion with the latest background profiles at each time step of the assimilating integration. The inversion would thus take on the role of the vertical analysis discussed by Lorenc et al. (1991). However this development may be overtaken by events if variational data assimilation is implemented.

(c) Further developments

(i) Climate data applications

Certain further developments in TOVS processing are primarily motivated by climate data applications, but may have benefits also for NWP. They may well be incorporated into the target system, and certainly if it is used in special data assimilations for climate research purposes.

The modelling of cloud radiative properties for use in the non-linear inversion has already been extended in experiments described by Watts and Baran (1992) and Watts (1993). The cloud drop effective radius is now being retrieved, essentially from the previously unused HIRS channel 19, and cloud radiative properties are being modelled more completely in an extended version of the forward model RTTOV. Further research is aimed at improvement of the treatment of ice cloud and retrieval of cloud optical depth (using HIRS channel 20). This use of reflected solar radiation in channels 19 and 20 requires improved modelling also of the radiative characteristics of the earth's surface.

As well as water vapour and cloud, other information on atmospheric composition can be extracted from TOVS data. Two important examples are total column ozone (obtained using HIRS channel 9) and sulphuric acid aerosol from volcanic eruptions (obtained using the differing channel 10s on NOAA 11 and 12 - see Baran et al., 1993).

(ii) Instrument developments

It is believed that the methods outlined here for TOVS data can be successfully extended to ATOVS (Advanced TOVS) data after the launch of NOAA-K, expected in 1995. The HIRS and AVHRR instruments will change only slightly whilst MSU and SSU will be replaced by the Advanced Microwave Sounding Units, AMSU-A and AMSU-B.

The complete information about the infrared spectrum from advanced instruments such as the IASI (Infrared Atmospheric Sounding Instrument) is an exciting prospect for the next century. As well as providing a basis for much higher vertical resolution in the temperature and humidity soundings, it seems likely that a much more detailed picture of surface characteristics and atmospheric composition will be obtainable. Once again, it is anticipated that the basic techniques

used in GLOSS will remain applicable, and that the main changes will be those necessary to handle the greatly increased volume of information.

(iii) Variational data assimilation

Early work with four dimensional variational data assimilation has shown great promise. Even when limited to the three spatial dimensions, variational assimilation has the attraction that it deals properly with the correlated errors of retrievals and NWP backgrounds that are inevitable in a system such as GLOSS. Current thinking is that a system similar to GLOSS will be required as part of the preprocessing of satellite sounding data before variational assimilation.

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